Technologies and R&D directions for trackers and calorimeters

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Energy Frontier Workshop – Restart

August 31, 2021

Introduction

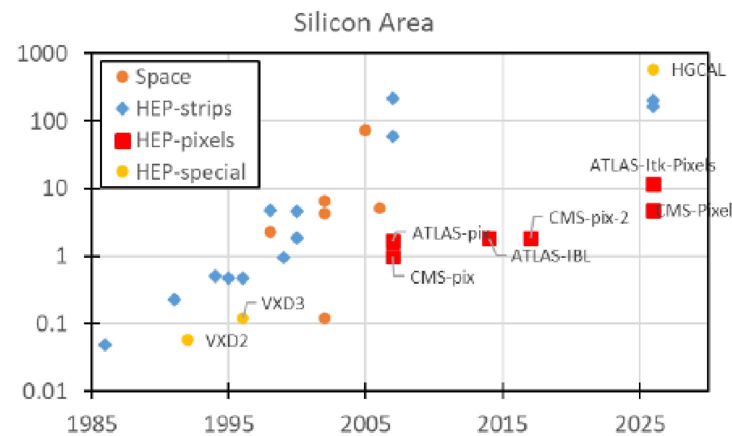
- Active community participation in IF03 and IF06 during Snowmass
  - Regular meetings with ~20-30 participants prior to the pause
  - Both IF03 and IF06 received about 60 LoIs, representing a broad spectrum from across the EF and beyond

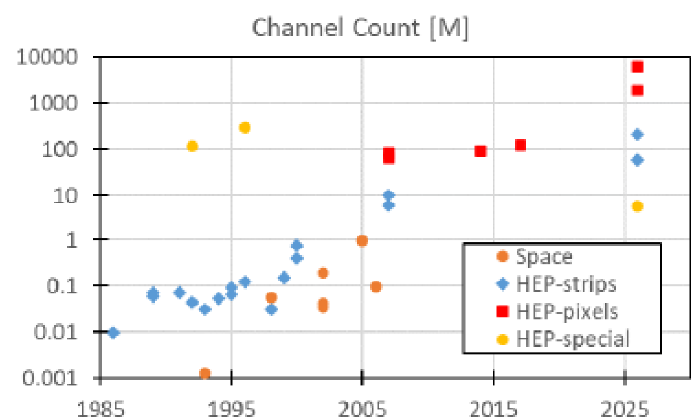
- We will overview the status of R&D in IF03 and IF06, and the outstanding R&D needs

- Motivations and physics drivers presented by C. Vernieri yesterday
  - https://indico.fnal.gov/event/49756

Experimental needs for trackers

- Many future and proposed experiments requir silicon trackers with ~0.1-1% X_0 per layers
  - Also, non-solid-state trackers, e.g., for high-intensity experiments.
- Extremely challenging while simultaneously:
  - Increasing segmentation and radiation tolerance
  - Enabling long lived particles, dense jet tracking
  - Improving timing precision
  - Increasing system size
  - Improving replaceability/maintenance
- Also, BRN listed priorities:
  - PRD18: High spatial resolution per-pixel fast timing (~10ps) timing
  - PRD19: New materials and processes
  - PRD20: Low mass scalable components and tracking systems





From V. Fadeyev

Holistic system design

- To achieve these goals, the system will have to be designed holistically from the start.
  - With limited person power and budgets, we need community endorsed plans to deliver the correlated R&D for future systems
  - Coherent design of sensor elements, FE readout, and advanced packaging
  - Services, cooling, power management considered early in design phase
  - Data reduction, on-detector event reconstruction necessary to stay with tight material budgets

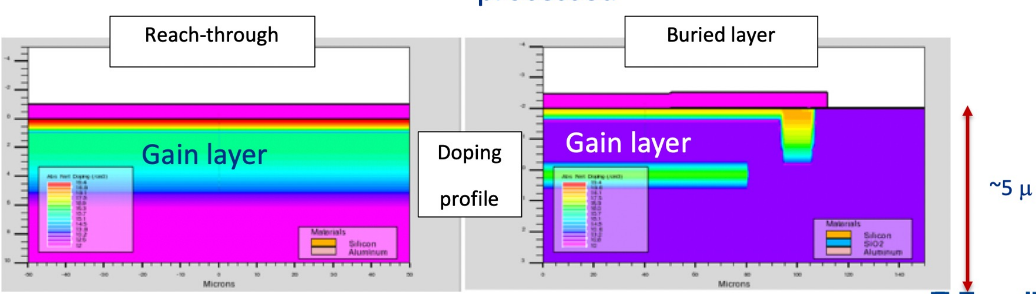
- The following slides attempt to list potential issues and solutions and inputs from the BRN, LoIs, presentations at IF meetings, and progress over the last year

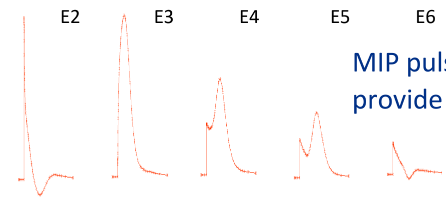
Ongoing efforts

- A snapshot of areas with active R&D for tracking applications
  - Low Gain Avalanche Detectors (LGADs): good timing, large pads
  - AC-LGAD: good position and timing resolution for MIPs
  - Monolithic detectors (HV/HR-CMOS) with embedded readout
  - Specially designed sensors to provide track position, angle and timing
  - Diamond detectors, 3D sensors, thin film detectors
- Common challenges for many technologies:
  - Services, cooling, low-power ASICs

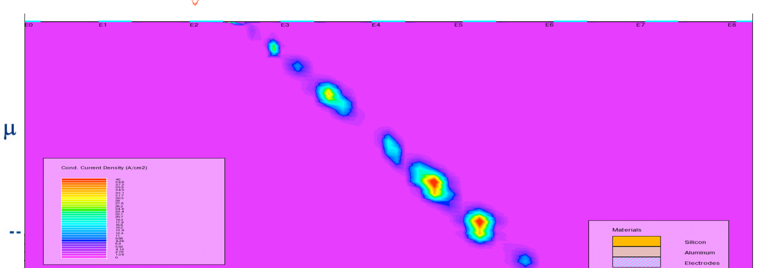
Usual reach-through implanted from top – limited options

Gain layer grown over implant – can be denser, top can be custom processed



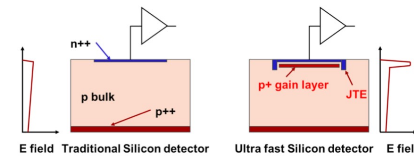


MIP pulse shapes – provide timing and angle

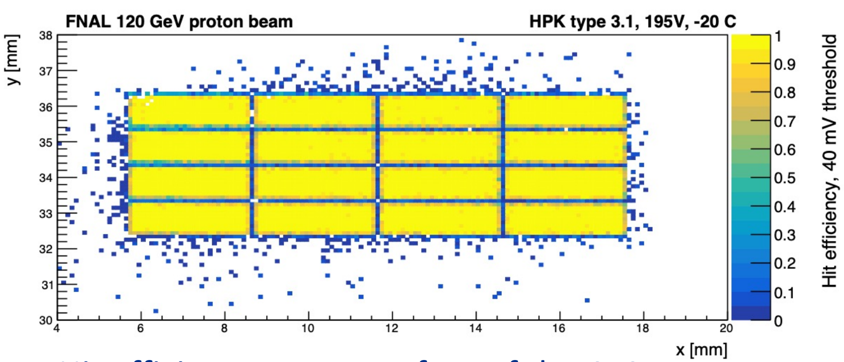


Advanced detector R&D for future experiments

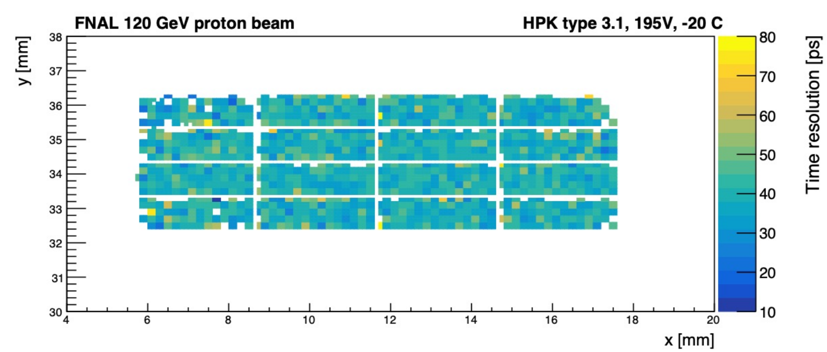
- A key breakthrough is the recent development of trackers with the addition of timing information: full 4-vectors (x,y,z, t)
  - Low-Gain Avalanche Detectors (LGAD)
  - Silicon detectors with internal gain



- Sensors developed for CMS and ATLAS show high degree of uniformity, excellent time resolution, rad hard up to **~3x10^{15} n/cm^{2}**
  - However, no-gain gaps between pixels: due to presence of JTE
- **Improve Gen-1 4D-trackers: achieve 100% fill factor, high position resolution**



Hit efficiency across surface of the 4x4 sensor

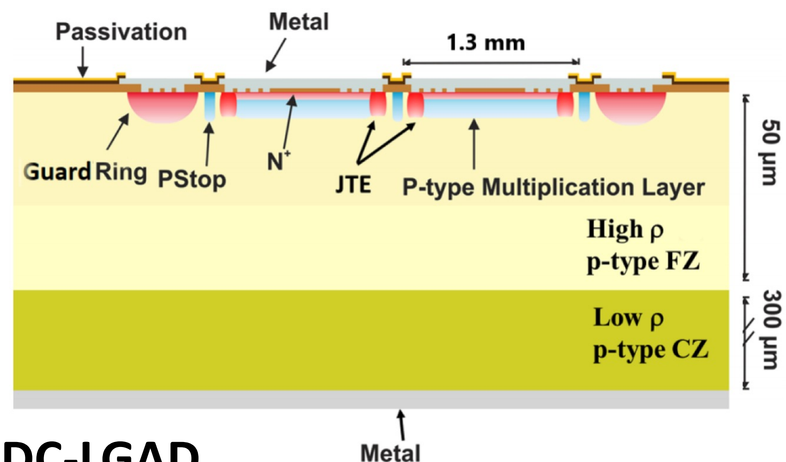


Time resolution across surface of the 4x4 sensor

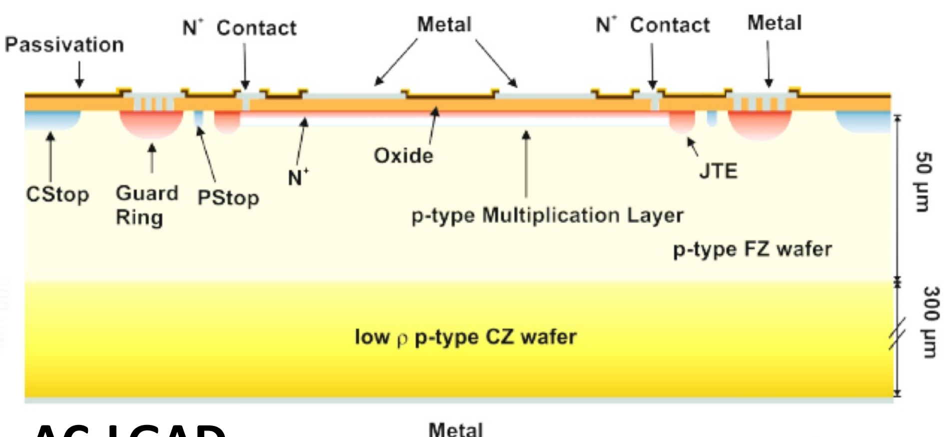
AC-coupled LGADs

- Ongoing R&D to eliminate dead area
  - Simultaneously improve position resolution via charge sharing
- Active R&D at different manufacturers (FBK, BNL, HPK, etc)
  - 100% fill factor, and fast timing information at a per-pixel level
  - Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.

Diagram credit: CNM



DC-LGAD

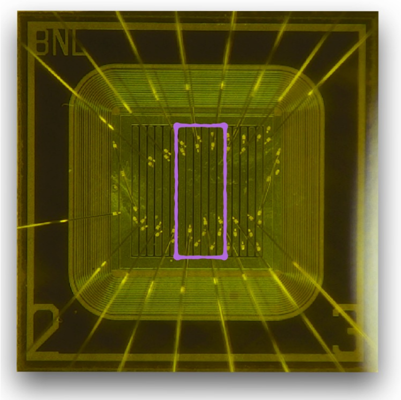


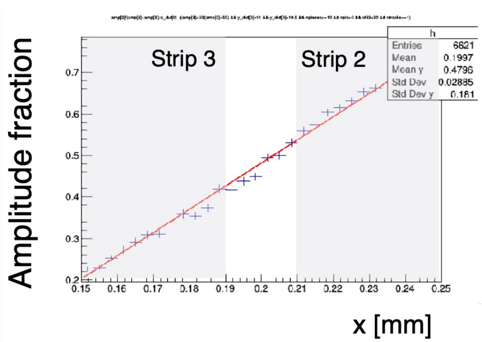
AC-LGAD

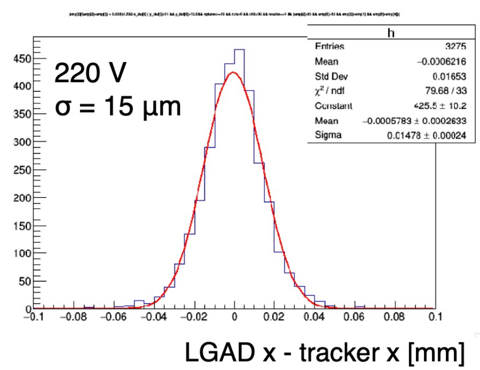
AC-LGAD measurements in beams

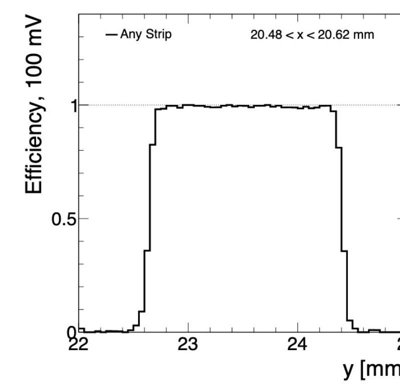
- Excellent performance in the beam showing high efficiency
  - First measurements in the beam in 2020:
- Time resolution and position resolution achieved targeted goals
  - 100% particle detection efficiency across sensor surface

100 micron pitch, 20 micron gaps









(b) Combined efficiency in y direction

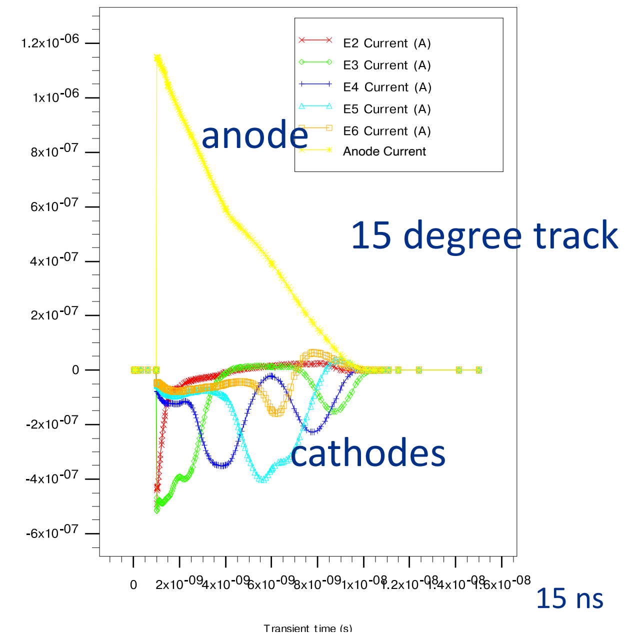
- Obtain < 5 micron resolution (considering 10-12 um reference)

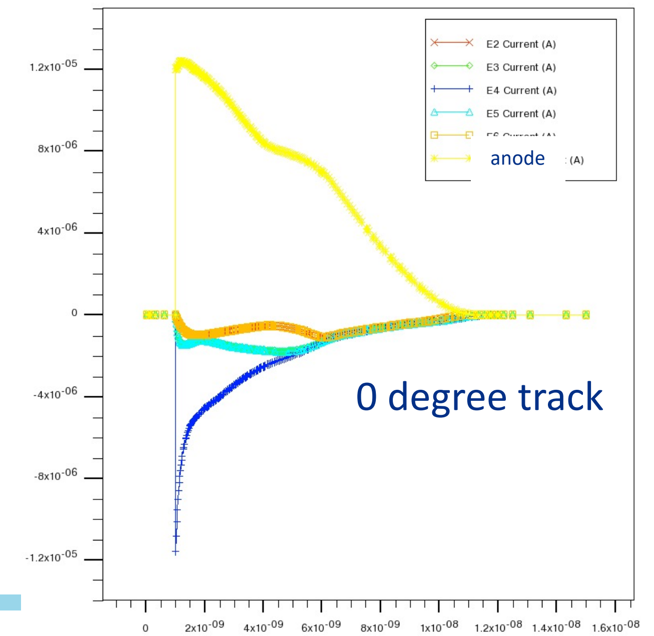
BNL strip AC-LGAD

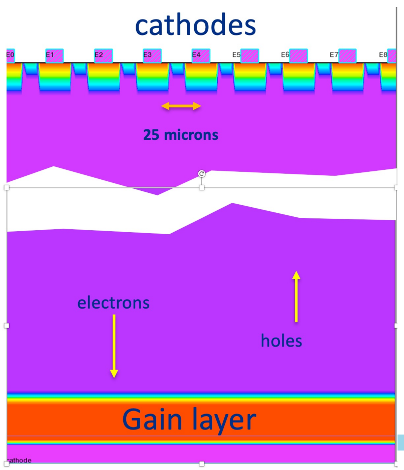
- **World first demonstration of sensor with simultaneous 30 ps and 5 μm resolution!**

Double Sided LGAD

- Low Gain Avalanche Diode with fine pixels on the hole-collecting side
  - Anode can provide timing with coarse pitch
  - Cathode subdivided into small pixels
- Records “primary” hole collection, then holes from gain region – double peak that reflects charge deposition pattern
  - Lower power due to large signal from the gain layer
- Resulting current pattern can be used to measure angle and position.



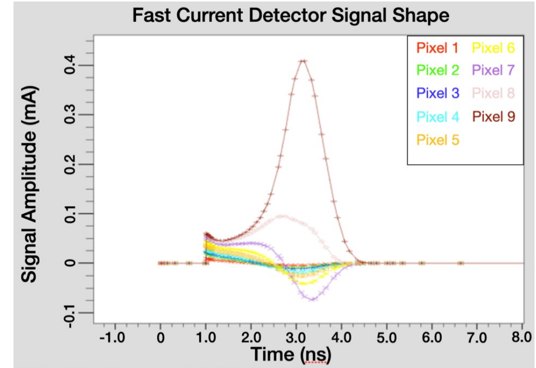


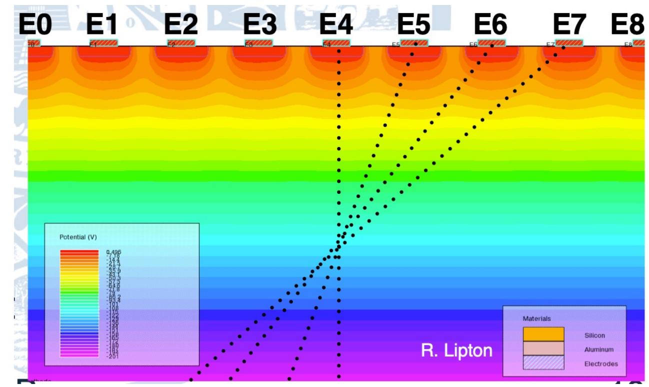


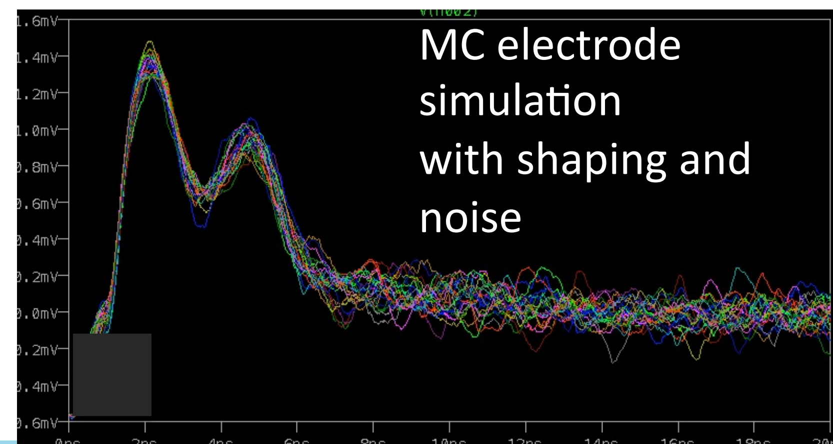
Induced currents sensors

R. Lipton, NIM A 945 (2019)
D. Berry CPAD 2021

- Induced current at a readout electrode from the instantaneous change of electrostatic flux lines
  - Signal is distinct from the drift current measured in traditional silicon detectors
  - Very fast rise time, can extract track angle from pulse shapes
- 4D tracking detectors + direction (X,Y,Z,T,θ)
  - Replace complex multi-layer modules
  - An ASIC with periodic current sampling could perform an on-chip angle measurement
- Can be used to create a track trigger at Level-1



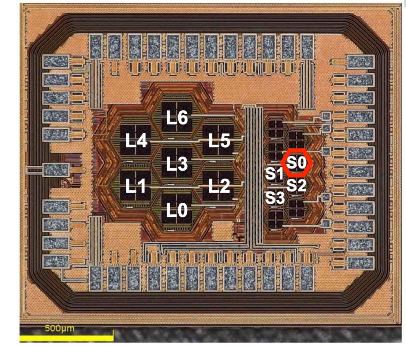




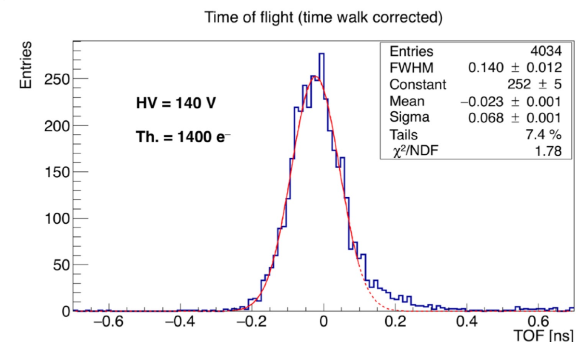
CMOS sensors

- Monolithic active sensors with embedded readout
  - Take advantage of electronics on top layer
  - Can achieve good signal-to-noise
  - R&D ongoing, developed for ATLAS, ALICE, RD50
- Monolithic AC-LGADs
  - Combine benefits of LGADs with monolithic process
  - Aim to fabricate prototypes with TJ 65 nm process
- Passive CMOS sensors

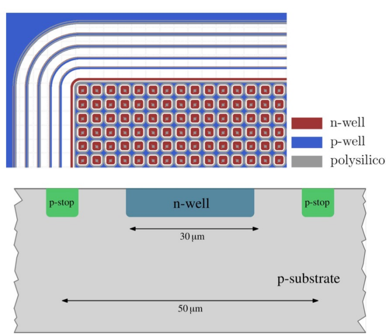
Small pixel S0, C = 70 fF

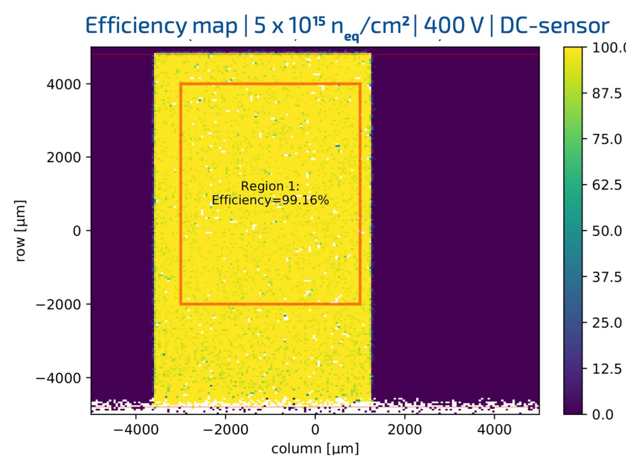


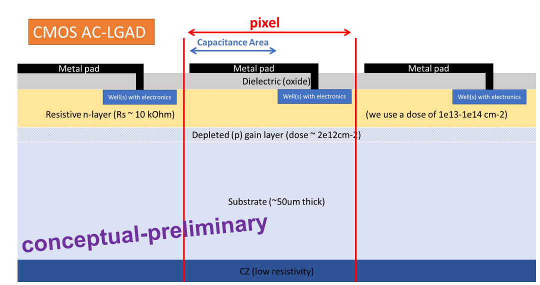
TT-PET chip: G. Iacobucci
October 4, 2019 CERN seminar



Time resolution≃ (46±2) ps





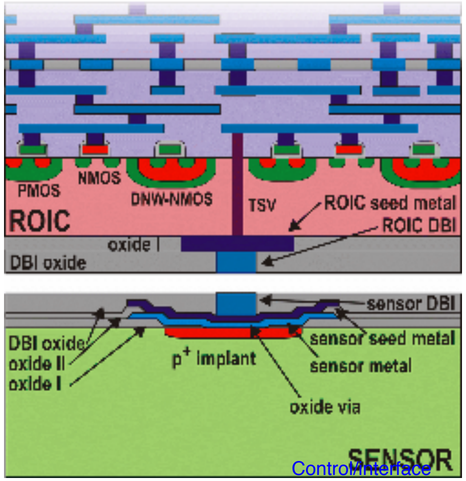


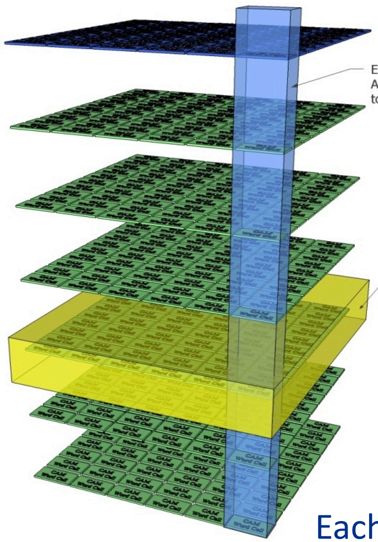
M. Baselga RD50, Y. Dieter RD50

G. Deptuch, Snowmass 2021

Integration/Packaging/Codesign

- Advanced integration of technologies on the front-end
  - AI/ML on-chip to extract features for fast tracking and L1 triggering, on chip clustering to readout reduce data volume
  - Wireless communication between chips/layers of trackers to form tracks/stubs/vertices
  - Novel materials to design more power-efficient data processing on the front-end
- Extensive 3D integration
  - Very fine pitch possible, multiple layers of electronics for sophisticated signal processing, vertically integrated
  - Possible to integrate different technologies, each optimized for separate tasks

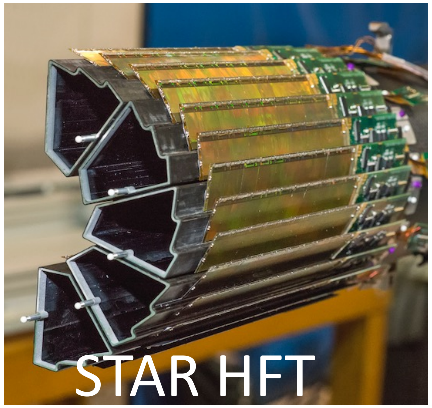


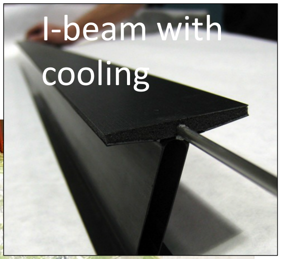


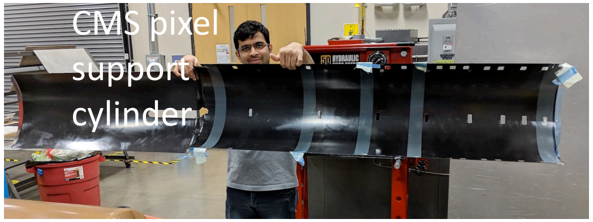
Fermilab

Mechanics, lightweight materials, cooling

- Integrated precision supports and cooling
  - Supports dominate at small eta, services at large eta
  - New layup, mold and curing methods need to be developed
- Aim to reduce %X0 all around
  - Hybrid systems have >2% X_0/layer with Si
  - MAPS achieves ~0.4 %X_0/layer with Si
  - Future MAPS systems target <0.3 %X_0/layer
- Future Hybrid Pixel systems are proposing to achieve under 1% X_0/layer with Si
  - Service reduction strategies for large eta coverage starts to become important



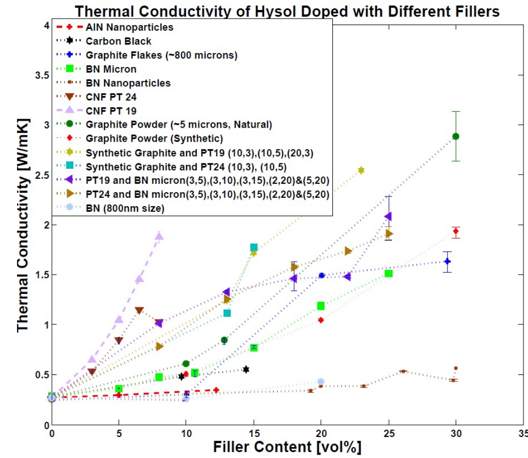




Mechanics, lightweight materials, cooling

E. Anderssen
Snowmass 2020

- Thermal services: Efficiently remove the heat 10-100s of kWs (~100-1000 mW/cm^2)
  - Air cooling difficult: low power/low duty cycle systems
  - Evaporative cooling will need continued improvements
    - At limit of coolant temperature with CO_2 (-45 C)
- Interfaces becoming limiting factor
  - Silicon-direct bonding, silicon micro-channels
  - Advancements in radiation hard thermal epoxies
- New Radiation Tolerant Materials
  - Materials processing into structures,
  - Maintain and enhance in-house fabrication capabilities
- Ties to Superconducting Magnets
  - One possible approach to reduce strains on the strands is stress management structures



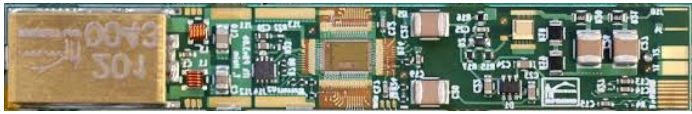
Survey of various fillers

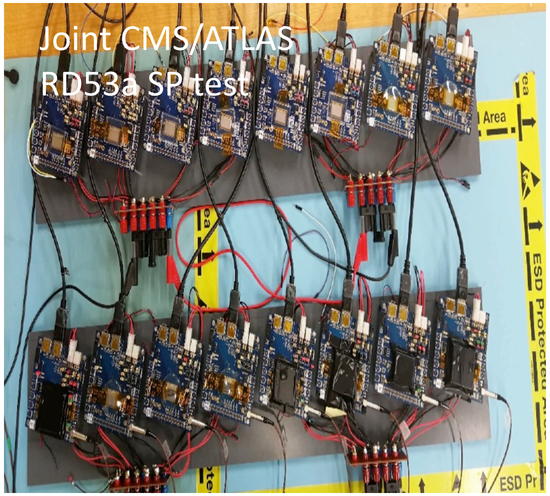
Rutherford Cable Insulation

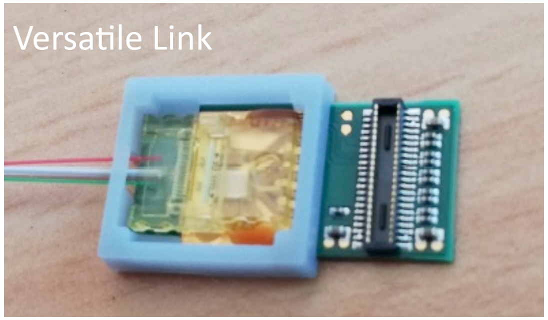
Electrical/Optical services

- Power services: Efficiently deliver thousands of amps for ASICs
  - DC-to-DC/serial powering
    - Improve conversion efficiency and rad hardness
  - Power pulsing may be possible for low duty cycle systems
- For HL-LHC, ATLAS pixels, data is 80% of service X_0 in forward direction
  - New lighter, radiation hard materials
- Or reduce the data volume going off-detector with on-detector processing, data compression,…
- Radiation hard optical drivers can reduce material on-detector as well

ATLAS DC-DC convertor







Experimental Needs for Calorimeters

- Detector designs moving towards a more integrated approach
  - Recording and combination of several type of signals

- BRN listed priorities
  - PRD1: Enhance calorimetry energy resolution for precision electroweak mass and missing energy measurements
  - PRD2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
  - PRD3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

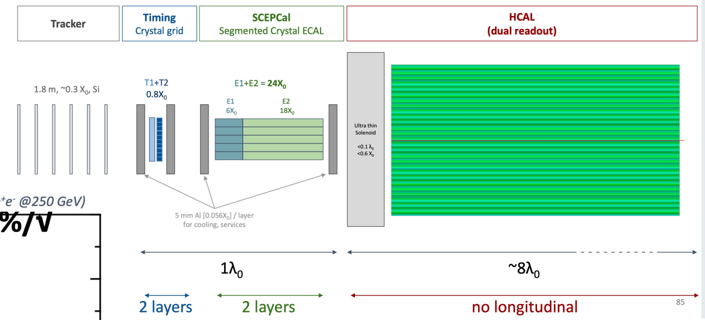
Experiments/Facilities using Calorimetry

- Colliders
  - LHC/HL-LHC, FCChh,…
  - Lepton Colliders – ILC, CLIC, CEPC, FCCee, …
  - EIC
- Neutrino experiments
  - neutrinoless double-beta decay (CUORE, nEXO)
  - MINOS, SuperNEMO, NovA
- Low Energy Experiments
  - Mu2e, EDM, rare decays
- Dark Matter Search Experiments
  - veto (e.g. LZ)
  - future G3 concept
- Experiments in Space
  - AMS

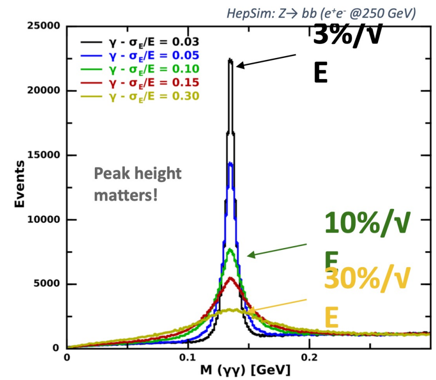
Technology Tools and Calorimetry Development Areas

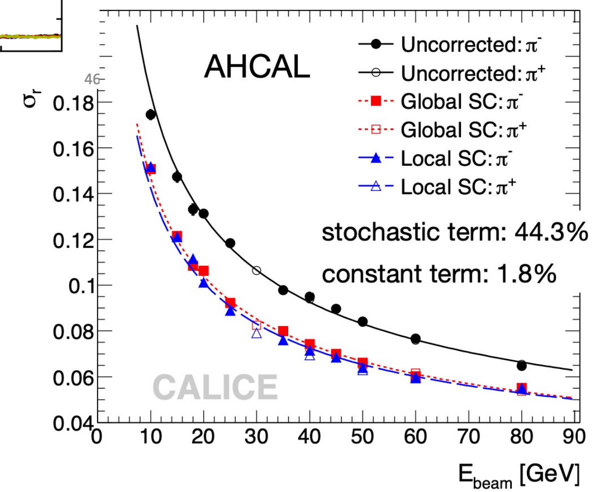
- Sampling, homogeneous calorimeters
- Materials for Calorimetry
  - high-Z, high-concentration,
  - metal-doped liquid scintillator, water-based liquid scintillator, and plastics scintillator,
  - hybrid liquid/crystal/plastics/glass, high-purity metal
- Energy detection mechanisms: scintillation, ionization, cryogenic (LAr, LXe, LKr…)
- Radiation Hardness
- Fast Timing
- Readout systems/transducers/noise
- Calibration/monitoring
- Triggers/DAQ

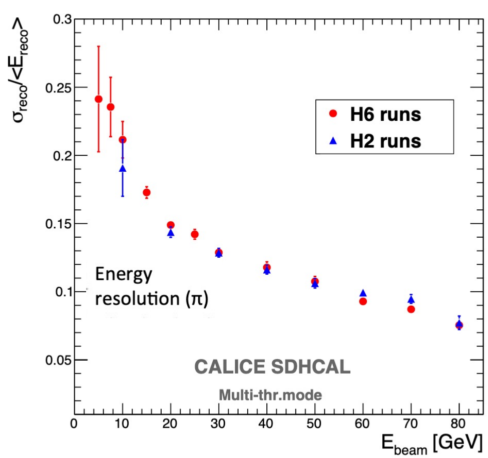
Performance studies

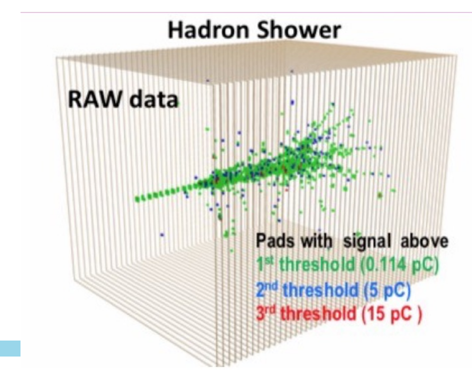


- Electromagnetic showers
- Hadron showers
- Single particles
- Particle ID in calorimeters (background rejection?)
- Timing studies
- Simulations vs calorimeter data
- Hadronic and electromagnetic energy resolution
- Pileup rejection



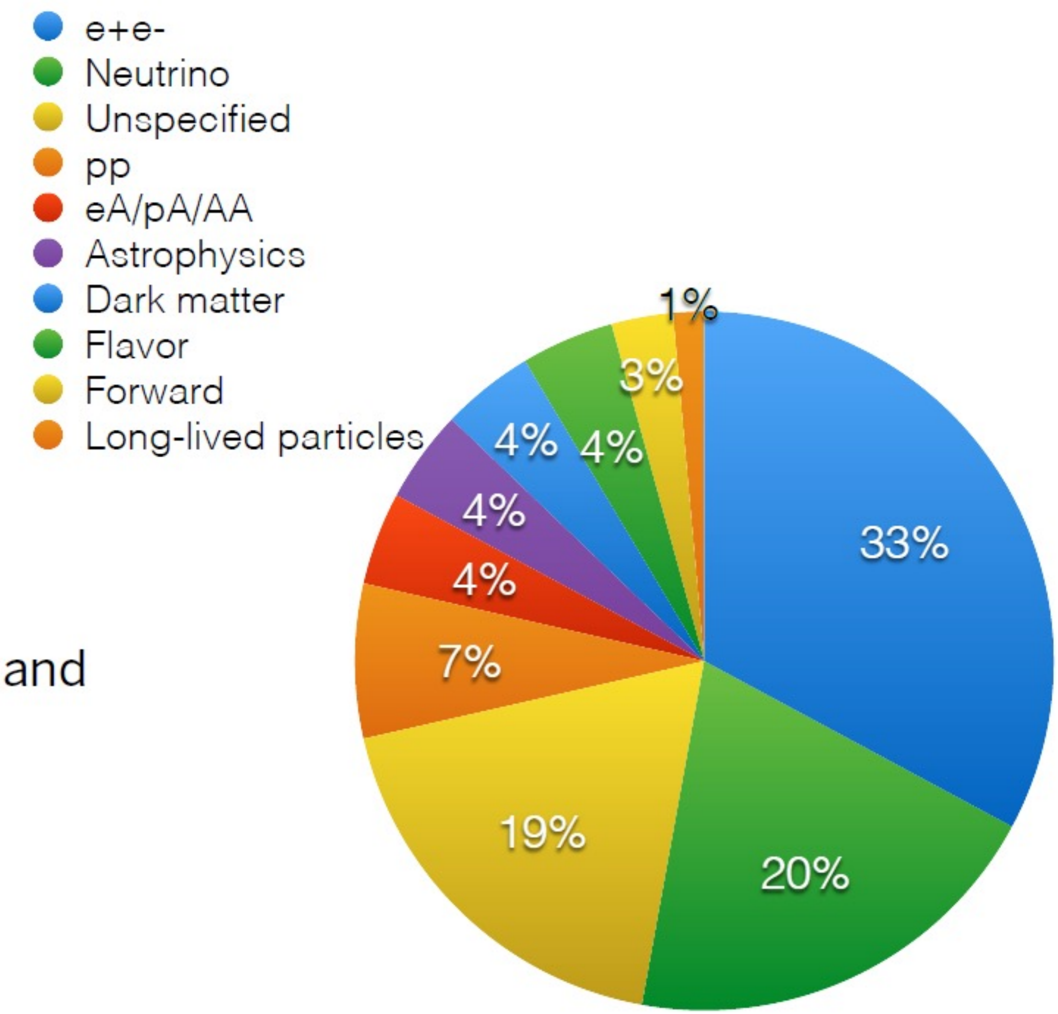






Physics topics

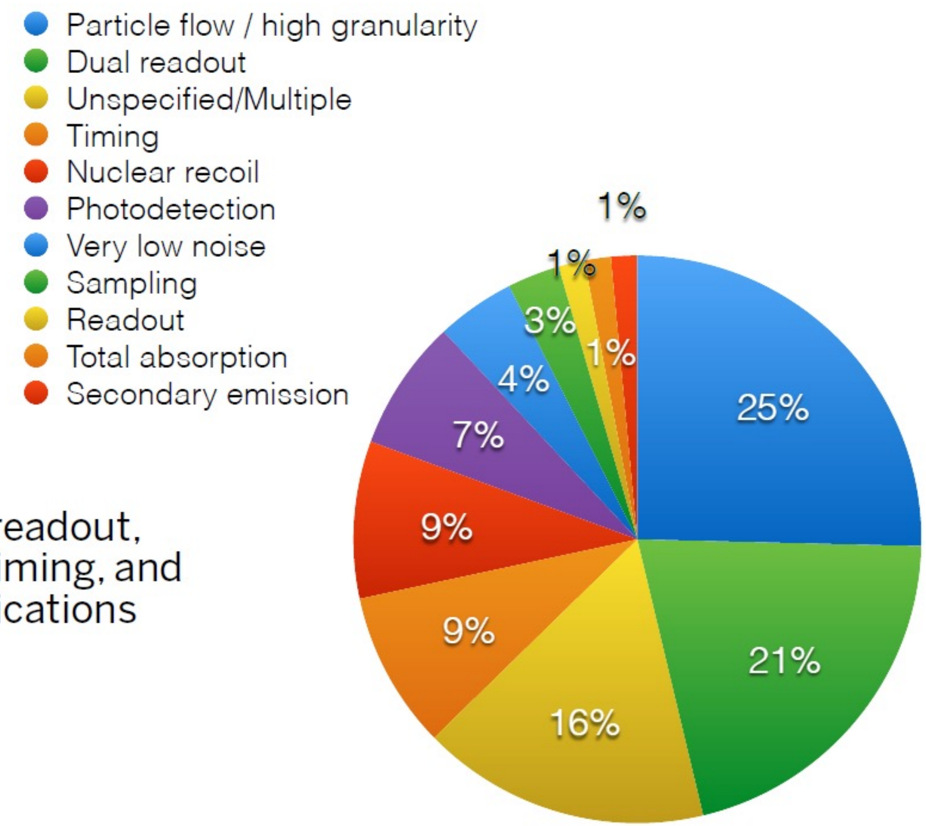
Breakdown from LoIs received



e^+e^-, generalized R&D, and neutrino applications dominate

Techniques

Breakdown from
LoIs received



Particle flow, dual readout, generalized R&D, timing, and nuclear recoil applications dominate

Electronics for calorimeter readout

- Media: silicon (e.g. CALICE, SiD Si-W ECALs), Scintillator (e.g. CALICE AHCAL), Crystals (BAF2), Gas (RPCs)
- Readout: PMTs, SiPMs, APDs
- Modes: Analog, digital, timing (LGAD, TDCs)
- ASICs: KPiX, HGCROC, SPIROC, SKIROC
- Dynamic Range
- Rates
- Radiation tolerance
- Material Profile
- Integration: sensor + readout, monolithics, vertical integration, interconnects, compact design
- Cost: development production

Calorimetry – R&D Areas examples

- Electromagnetic calorimeters
  - digital vs. Si-based analog
  - new crystal materials
- Hadron calorimeters: sampling vs. dual readout
- General
  - timing layers: extra dimension to resolve shower components, suppress background(s)
  - local intelligence: track following
- Machine learning approach to faster simulations
- Radiation hard elements for low-angle/forward calorimeters

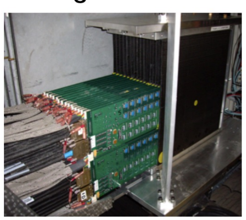
- A few samples of the vast R&D in the following slides

Si Based Calorimeters in Current and Future Experiments

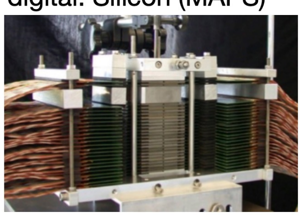
- HGCal in CMS: first generation implementation of many decades of R&D in this direction
- To fully exploit the potential of highly granular calorimeter systems:
  - Extreme compactness, in particular in ECAL, minimal “dead space”
- For the full calorimeter systems, this imposes a number of requirements:
  - Both ECAL and HCAL inside solenoid
  - Fully integrated electronics to support high granularity
  - Ultra low power to reduce or eliminate cooling needs, complex power distribution to support high currents during power pulsing w/o significant voltage drop
- Very compact interfaces: data concentration, calibration, services

Electromagnetic - Tungsten absorbers

analog: Silicon and Scintillator/SiPM



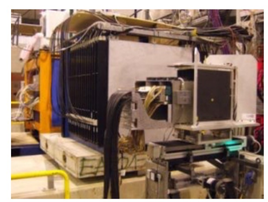
digital: Silicon (MAPS)



39 Mpixels in 160 cm^2

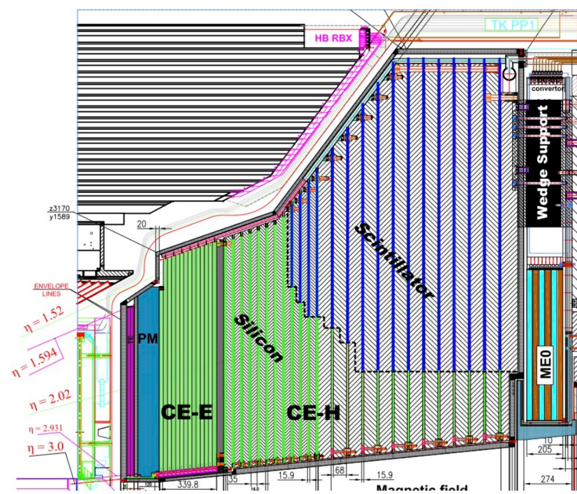
Hadronic - Steel and Tungsten absorbers

analog: Scintillator/SiPM (Fe and W)



(Semi)digital: RPCs (Fe, W digital only)

+ few-layer SD prototype with Micromegas

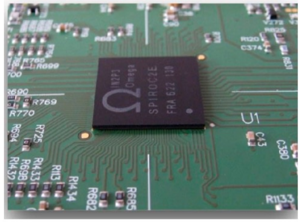


F. Simon Snowmass 2021

Si Based Calorimeters in Current and Future Experiments

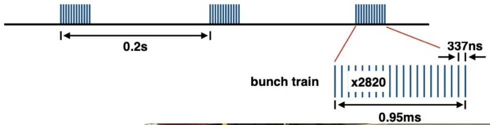
Physics prototypes

integration

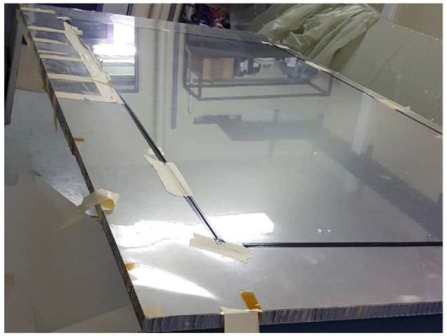


scalability to large areas, automatisation

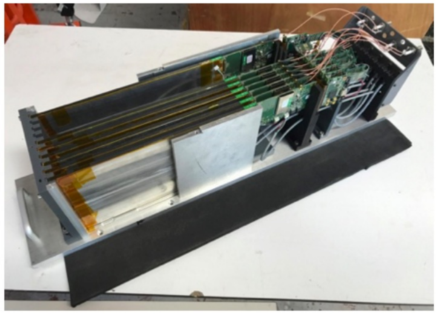
- Common to all new developments: Embedded electronics, power pulsing

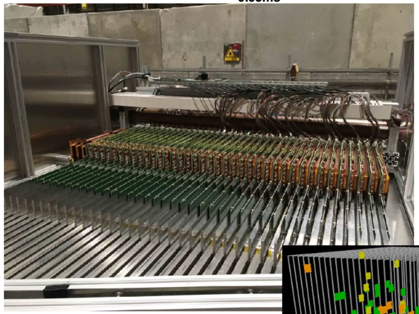


Large RPCs
SDHCAL prototype

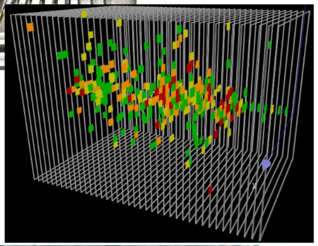


SiW ECAL prototype





AHCAL prototype



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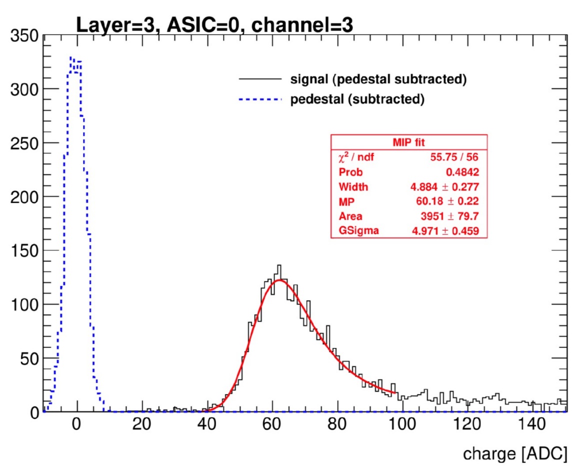
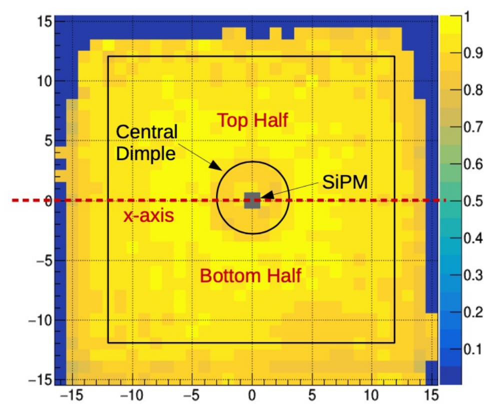
Si Based Calorimeters in Current and Future Experiments

- SiW ECAL: full 15 layer prototype available (15k channels)
  – Going into test beam this year, using “Higgs-factory” technology
  – Excellent performance of detector channels
- Analog HCAL with SiPM-on-tile
  – Fully integrated detector with embedded front-end electronics
  – Detector tested extensively in particle beams at DESY & CERN
- Semi-digital HCAL: RPC with integrated electronics



SiW ECAL



SiPM on tile HCAL

Semi-digital HCAL

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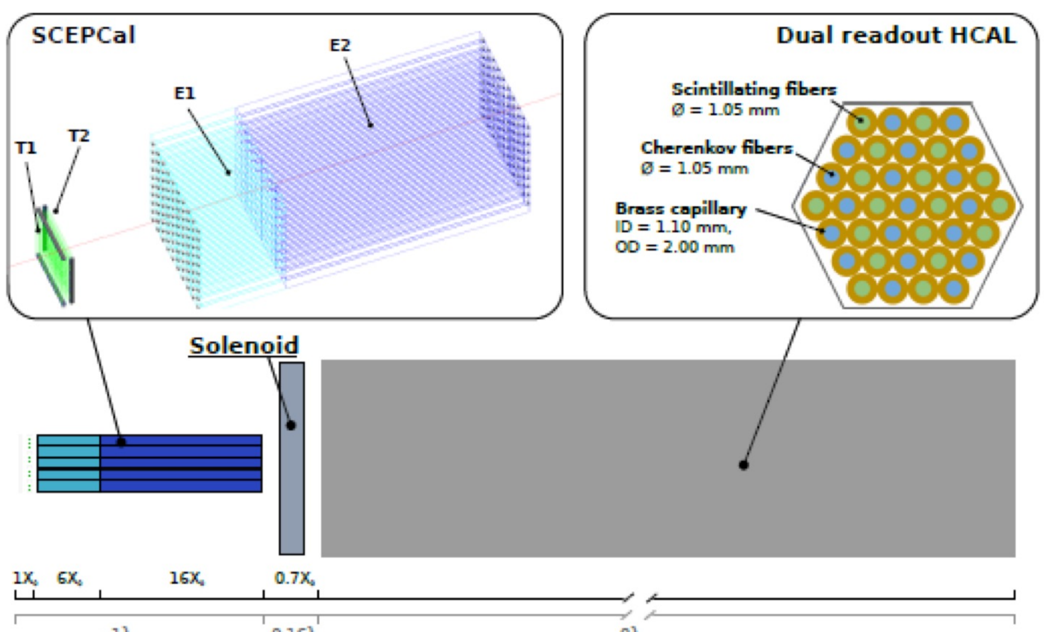
Dual readout calorimeters

- Use Cherenkov light to measure, shower-by-shower, the fraction of the shower energy in π^0s.
  - Use scintillation light to measure all ionizing energy deposits. Apply a scale correction that depends on this ratio.
  - Get sampling terms of 3% for electrons/photons and 30% for hadrons
- Following on RD52 work: upgrading for new developments in inexpensive, high-QE, tailored-wavelength SiPMs

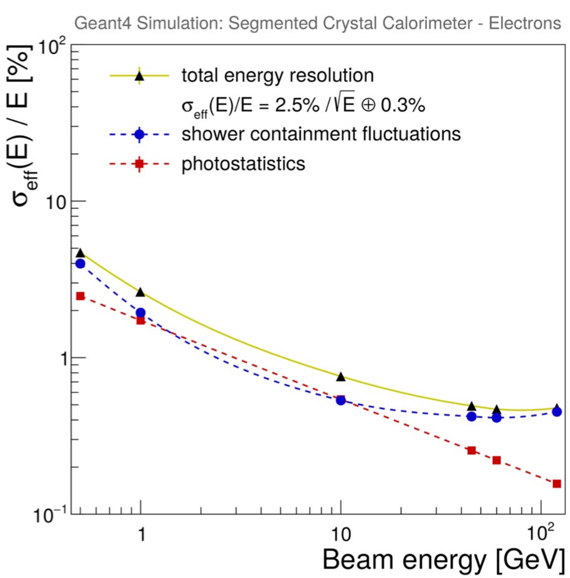


S. Eno, Snowmass 2021

Dual readout calorimeters

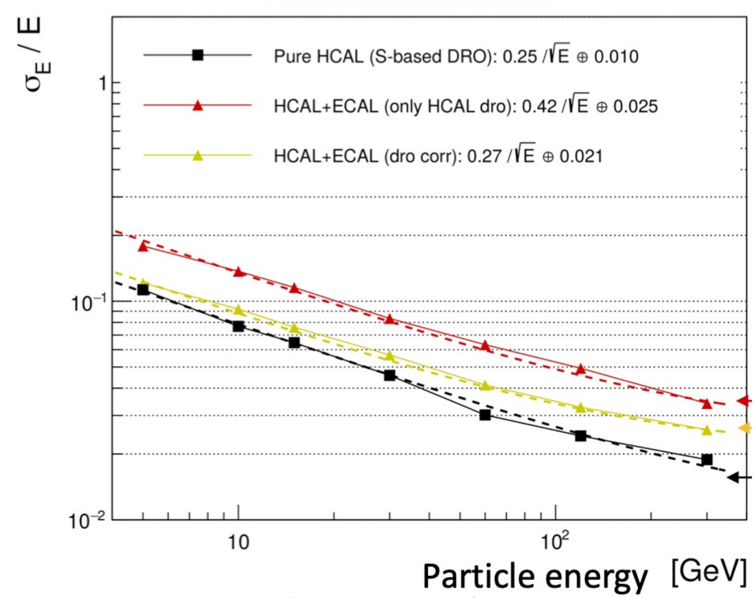
- Many technological advancements in the field of photodetectors
  - Cheap, compact and robust SiPMs with small cell size
  - Detect Cherenkov photons in the UV (BGO) or infrared region (PWO)
- Deliver excellent EM and jet resolutions for Higgs Factory

$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$



SCEPCAL e.m. resolution

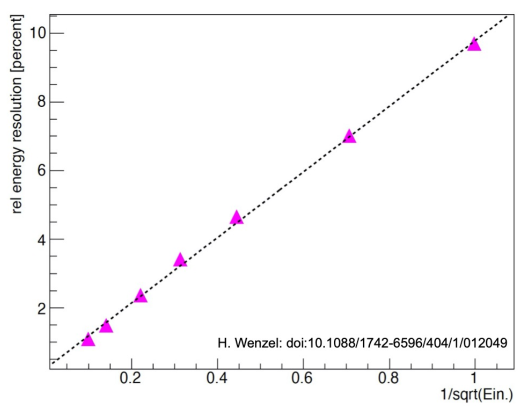
$\sim 27\%/\sqrt{E} \oplus 2\%$



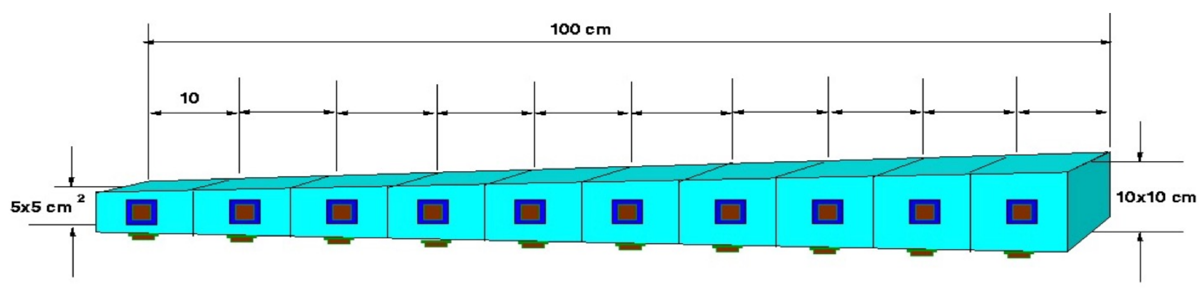
Hadronic resolution

Total absorption HHCAL

- Measure fraction of EM energy event by event by comparing signals from scintillation light and Čerenkov light
  – No sampling fluctuations or other sampling-related contributions.
- Technical advances make this option viable with further R&D
  – Low form factor photo-detectors that can operate in a magnetic field (SiPM)
  – High density scintillating crystals/glasses (λ~20cm)
- Dense scintillating materials and compact photodetectors promise construction of HAD calorimeters with energy resolution reaching 10%/√E



MC simulation of single particle response



M. Demarteau, CPAD 2021

Summary

- Significant need for detectors for future collider experiments
- We need to work together to find solutions
  - Time to start is now: R&D timescale of 10-20 years to develop technologies for LHC and HL-LHC systems
  - Will require extra R&D funds (BRN, base grants, LDRD), industry-academic partnerships (SBIR,..)
- How do we develop to our future needs through near term experiments?
- How do we organize? How do we maintain and develop expertise and facilities?
- Next step for SNOWMASS process will be to define and outline Whitepapers